Hydrogen Ion Cyclotron Wall Conditioning for Fuel Removal on TEXTOR and ASDEX Upgrade

T. Wauters[1], D. Douai[2], A. Kreter[3], A. Lyssoivan[1], S. Möller[3], V. Philipps[3], V. Rohde[4], V. Bobkov[4], K. Crombé[1], M. Freisinger[3], D. Kogut[2], R. Koslowski[3], D. Nicolai[3], J.-M. Noterdaeme[4,5], M. Rubel[6], G. Sergienko[3], M. Vervier[1], M. Van Schoor[1], the TEXTOR team and the ASDEX Upgrade Team

[1] *LPP-ERM/KMS, Association Euratom-Belgian State, 1000 Brussels, Belgium*

[2] *CEA, IRFM, Association Euratom-CEA, 13108 St Paul lez Durance, France*

[3] *IEK-4 (Plasmaphysik) FZ Jülich, Association Euratom-FZJ, TEC, 52425 Jülich, Germany*

[4] *Max-Planck Institut für Plasmaphysik, Euratom Association, 85748 Garching, Germany*

[5] *Ghent University, Faculty of Engineering, 9000 Ghent, Belgium*

[6] *Alfvén Laboratory, KTH-EE, Association EURATOM-VR, 10044 Stockholm, Sweden*

Introduction

Ion Cyclotron Wall Conditioning (ICWC), applicable in presence of the toroidal magnetic field, is envisaged in ITER to recover from disruptions, leaks and torus vents, for recycling control and for fuel removal [1]. Various experiments on different devices as well as modeling efforts are advancing to consolidate this technique [2, 3, 4, 5]. This contribution focuses on a selection of recent hydrogen ICWC experiments on ASDEX Upgrade and TEXTOR. The ASDEX Upgrade experiment aimed at comparing isotopic exchange efficiencies previously obtained on Carbon devices [5] to the ITER relevant Tungsten wall. The experiment on TEXTOR aimed at assessing the performance of H_2-ICWC for codeposited layer removal. The latter being a particular important fuel removal aspect since it is predicted that a major part of tritium in-vessel inventory build-up on ITER will be due to the formation of tritium rich codeposited layers [6].

Isotopic exchange experiment on ASDEX Upgrade

Isotopic exchange results obtained on carbon machines TORE SUPRA, TEXTOR and JET ([2, 5] and references herein), have illustrated that hydrogen ICWC can remove significant amounts of hydrogen isotopes from the wall within short time scales. It was found that the re-occuring 2 to 3 times higher retention of the discharge gas can be drastically minimized by optimizing the RF duty cycle. This optimization of the RF pulse length and the time interval between subsequent pulses leads both to an (i) *improved removal efficiency of wall desorbed molecules* by vacuum pumps and a (ii) *limited retention of discharge gas* into the plasma facing components.

Recent isotopic exchange experiments on tungsten ASDEX Upgrade evidenced comparable removal efficiencies as obtained on the Carbon machines. Within 14 H_2-ICWC discharges with cumulated discharge time of 51 s, $7.3 \cdot 10^{21}$ D particles could be removed, corresponding approximately to 12 monolayers. The discharges contained max. two RF pulses with variable pulse lengths (50 ms to 10 s), $P_{\mathrm{RF,gen}} = 100-600\,\mathrm{kW}$, $f_{\mathrm{RF}} = 30\,\mathrm{MHz}$ in monopole phasing and dipole phasing, $B_{\mathrm{T}} = 1.9-2.3\,\mathrm{T}$ and continuous gas injection to obtain $p_{\mathrm{H_2}} \approx 2 \cdot 10^{-4}$ mbar in absence of plasma. Just as on the carbon machines, also on ASDEX Upgrade the additional retention of hydrogen into the walls was significant, $3.5 \cdot 10^{22}$ H, and the ratio retained/removed could be improved by optimizing the RF duty cycle; e.g. the advantage for applying shorter RF pulses instead of continuous RF discharges is clearly illustrated on Fig. 1, giving the H_2 and HD partial pressure time traces for four similar RF discharges with different pulse lengths. As the gas injection was continuously constant, the gas consumption by the walls is not compensated by extra injection which is clearly visible from the H_2 pressure drop on switching on the RF power. The longer the RF pulse, the deeper the pressure drop, until at $t \approx 1$ s a steady state pressure level is formed. The HD partial pressure first starts to increase on switching on the RF power, illustrating the strong wall interaction, while for the longer RF pulses at $t > 250$ ms it decreases again due to the drop of the total pressure; for these pulses, a large part of the initial wall released HD will be reimplanted into the wall. The optimal pulse length in this figure is the pulse of 250 ms; the maximum p_{HD} is reached, whereafter the discharge is stopped and the outgassed HD can be recovered from the vessel by the pumps ($Q_{\mathrm{HD,pumped}} = p_{\mathrm{HD}} S_{\mathrm{HD}}$, with S_{HD} the pumping speed of HD). An analysis of the coevoluting pressure, density, coupled RF power, wall fluxes and retention rate time traces, supported by 0D ICWC plasma modeling, can be found in [7].

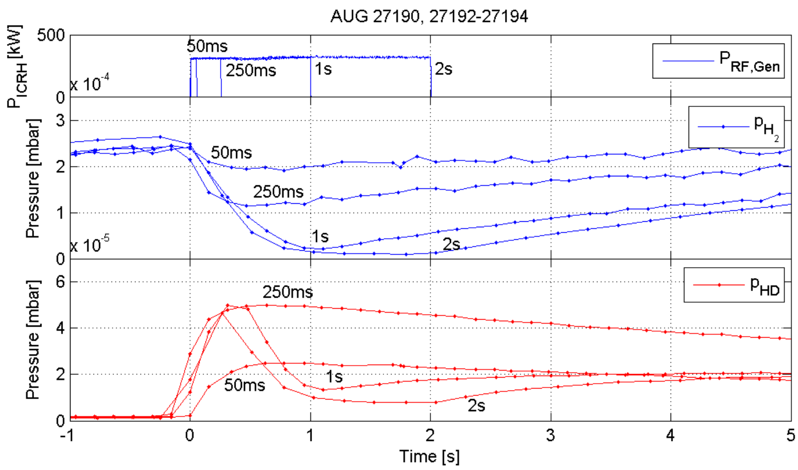

Figure 1: Partial pressure time traces ($p_{\mathrm{H_2}}$ and p_{HD}) for 4 similar ASDEX Upgrade discharges with different pulse lengths; continuous constant H_2 injection, $P_{\mathrm{RF,Gen}} = 300\,\mathrm{kW}$ (monopole phasing), $f_{\mathrm{RF}} = 30\,\mathrm{MHz}$ and $B_{\mathrm{T}} = 2.3\,\mathrm{T}$.

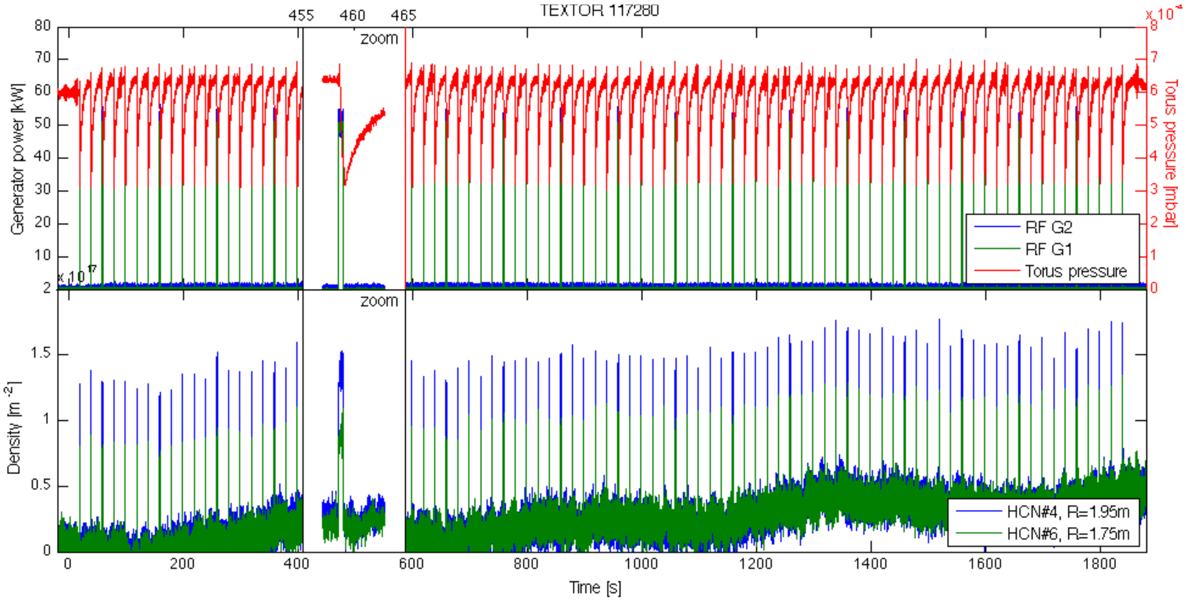

Figure 2: Multi-pulse H_2-ICWC procedure on TEXTOR (#117280) counting 92 RF pulses of 0.5 s, a pulse cycle of 20 s, $B_T = 0.23\,T$, $f_{RF,G1} = 29\,MHz$ and $f_{RF,G2} = 38\,MHz$. Top figure: RF generator power and torus pressure; bottom figure: line integrated HCN density.

Multi pulse H_2-ICWC on TEXTOR

To assess the feasibility of employing ICWC for deposited layer removal pre-characterized a-C:D layers on silicon were exposed to multi pulse H_2-ICWC discharges on TEXTOR to quantify erosion and redeposition at surfaces both parallel and perpendicular to the magnetic field lines. For the experiment a dedicated staircase-like heated (320 °C) sample holder was developed, equipped with a perpendicular Langmuir probe and a surface probe, and mounted into the bottom limiter lock on TEXTOR, ensuring that the radial locations of the upper installed samples were well out of the shadow of the poloidal limiter ($r < 48\,cm$). The ability of maintaining a steady state toroidal magnetic field below 0.4 T on TEXTOR allowed to perform long series of ICWC pulses. RF pulses of 0.5 s have been repeated every 20 s maintaining constant discharge parameters (see e.g. Fig. 2); $p_{H_2} \approx 6 \cdot 10^{-4}\,mbar$ (continuous flow), $B_T = 0.23\,T$ (i.e. TEXTOR high harmonics ICWC scenario [3]), $P_{RF,gen} = 2 \times 50\,kW$, while the wall was preconditioned with H_2-GDC to facilitate quantitative analysis of the isotopes removed from or redeposited on the installed a-C:D samples. The longest pulse set counted 185 subsequent RF discharges, representing a H_2-ICWC conditioning procedure of approx. 1 hour. The total plasma exposure time of the samples is estimated at 242 s (from HCN data), by in total 490 RF pulses. From the insignificant heating of the antenna structure and the absence of RF trips nor the detection of metallic characteristic radiation, it was concluded that the RF systems worked safe and reliably throughout the whole conditioning procedure.

Ellipsometry analysis of the exposed layers showed net erosion of all parallel exposed samples at $r = [44, 45.5, 47, 48.5]$ cm, and no clear radial dependency could be found: erosion of $[66, 65, 56, 74] \pm 3$ nm respectively. For the perpendicular samples at the outer radial positions the net erosion is found to be higher, whereas erosion-deposition gradients were found at radial locations closer to the plasma center ($r < 48$ cm) indicating a competition between erosion and redeposition which is yet to be studied further: $r = [44.75, 46.25, 47.75, 49.25]$ cm with respective erosion of $[90 : -26, 134 : -24, 122, 118] \pm 3$ nm. Assuming constant erosion rates, and taking into account the total duration of the multi pulse conditioning procedure (2.7 hours) the erosion rate can be estimated at $0.4\,\mathrm{nm/min}$, which is of the same order as obtainable with CW H_2-GDC [8]. Taking a standard carbon surface density of $6.6 \cdot 10^{15}\,\mathrm{C/cm^2 nm}$ and a D/C concentration of 0.4 [6], this translates into $2.6 \cdot 10^{15}\,\mathrm{C/cm^2/min}$ or a deuterium mobilization from codeposited layers of $1.1 \cdot 10^{15}\,\mathrm{D/cm^2/min}$. The erosion yield is estimated at $0.027\,\mathrm{C/H^+}$, from the ion saturation current of $(6.8 \pm 0.3) \cdot 10^{16}\,\mathrm{H^+/cm^2}$, measured by the surface probe at $r < 48$ cm and assuming a predominant H^+-ion flux [9]. The latter ion flux is at least 2 orders of magnitude higher than for standard TEXTOR H_2-GDC [4], while the yield-value is typical for impact energies above 20 eV [10]. Additional surface analysis results can be found in [11].

Conclusion

Isotopic exchange experiments on ASDEX Upgrade have shown comparable efficiencies as on Carbon machines. RF duty cycle optimization could be employed to optimize the ratio of removed over retained hydrogen isotopes. A multi pulse H_2-ICWC experiment on TEXTOR, exposing a-C:D layers to 490 0.5 s ICWC pulses was presented, delivering a value for the carbon erosion yield and illustrating the removal efficiency of codeposited layers for fuel removal.

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